PLASMA MICROMACHINED MEMS
FOR INTELLIGENT DIAGNOSTIC SENSORS

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Abstract: Microelectromechanical Systems (MEMS) is a new technology rapidly gaining in commercial acceptance. In MEMS, integrated circuit processing technology is utilized to fabricate silicon microstructures that are released from the underlying substrate such that they are free to move in one or more dimensions. This technology therefore enables the integration of mechanical and electronic components in a single integrated circuit style device.

MEMS is an ideal technology for intelligent diagnostic sensor applications. It provides the capability for high resolution sensors for a variety of physical phenomena (e.g.,, pressure and acceleration) in a small package with integrated electronics. In volume production, MEMS devices can reach low unit costs enabling large arrays of such devices to be used in practical industrial monitoring applications. On-chip electronics increases device intelligence as well as offering the possibility of remote sensing and local decision making.

TMS Technologies' proprietary plasma micromachining technology offers superior performance and reduced manufacturing costs when compared to other MEMS processes in use at the present time. It is hoped that cost effective machine diagnostic sensors can be developed by bringing the capabilities of plasma micromachining to the attention of the failure prevention community through forums such as the *1996 Technology Showcase.*

Key Words: Machine diagnostics; MEMS; micromachining; plasma etching; power generation; sensors; vibration analysis

Introduction: Maintenance of large industrial equipment presents both a technical challenge and a major expense in many industries. Of particular concern in most situations, such as power generation, military systems, or petrochemical plants, is the prevention of unexpected outages. Such equipment failures can be catastrophic in their impact on human life, the environment, and the financial position of the operating company. In the most demanding of applications, e.g., a nuclear power plant, very costly technologies can be employed to ensure continuous monitoring of the health of major equipment. In most other applications, fiscal reality constrains the tools that can be applied to this problem. One most often finds labor intensive preventative maintenance rather than real-time monitoring. Such routine maintenance is deliberately chosen to take place frequently enough to ensure emerging problems are detected and repaired prior to their resulting in equipment failure. Although this can be an effective solution, it is time consuming, results in excessive equipment downtime, is not fool proof, and provides little information on real-time correlations between operating conditions and failure modes. A far superior solution would be to obtain a cost effective technology for real-time machine diagnostic monitoring and condition based maintenance [1].

This paper is concerned with the use of a new microfabrication technology to produce intelligent sensors for use in machine diagnostic applications. To provide a specific context we will consider the case of vibration analysis of heavy rotating equipment, such as found throughout a power generation plant. This type of equipment exemplifies the maintenance issues being discussed and is prevalent in many industries. However, the diagnostic technology described herein and the issues surrounding its use in industrial applications, are applicable to a much broader scope of machine maintenance situations.

Background: The following specific examples, and the general observations drawn from them, are based on visits by one of the authors to several electric power generation plants. In the case of rotating equipment found throughout such plants, vibration analysis [2] can provide critical information as to the health of the equipment and can be used to predict a variety of failure modes. Currently available systems utilize either case mounted accelerometers or shaft position (gap) measurements to determine relevant vibrational information. Data from these sensors are either provided in real-time or sampled at some regular interval. In most instances, if a certain threshold value of vibration is detected an alarm is indicated and maintenance personnel are brought in to ascertain the nature of the problem and to initiate corrective measures.

Consider the specific case illustrated in Figure 1. This data represents the annual maintenance expenditures, both preventive and corrective, on several medium size exhaust fans in an electric power generation plant. The actual dollar value of the expenditures has not been shown. However, the relative magnitudes do illustrate of the real situation that was observed. During the first seven years, no effort was made to measure vibration on the fans. In year eight, after experiencing severe increases in maintenance expenses, the vibration of the fans was periodically monitored with a portable instrument (sensors were not permanently affixed to the fans). This relatively simple condition based maintenance effort resulted in a five-fold reduction in maintenance expenditures in that year.

Largely as a result of the expense of presently available vibration monitoring equipment, and the cost of retrofitting such sensors to existing rotating equipment, real-time vibration analysis has not attained widespread acceptance. Rather, the approach has been to make periodic inspections and measurements with portable vibration monitors such as in the fan case above. To ensure that the power plant meets its reliability objectives, substantial redundancy was built into the plant's systems and a very large inventory of spare parts is maintained on site. Such an approach effectively meets the objectives but at a very high cost. In the case of power generation this cost is partially masked by the regulatory environment in which the industry is currently operating. For other industries, such capital expenditures would not be a viable approach to meeting equipment availability objectives.

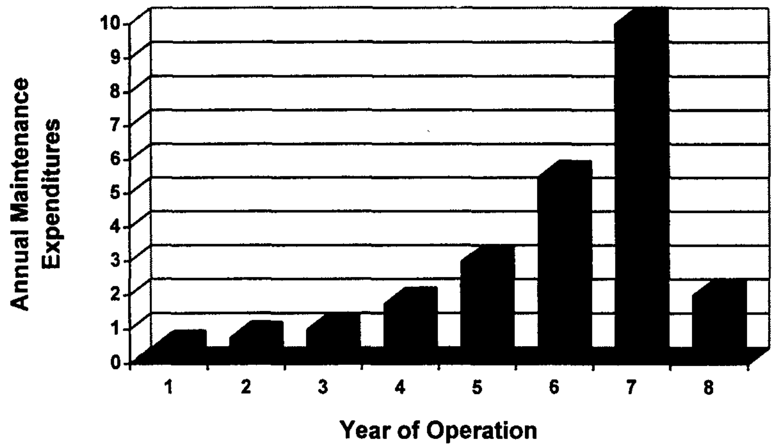

Figure 1. Maintenance Expenses for Exhaust Fans

A natural question therefore is why is vibration monitoring equipment so costly. The answer to which relates to the nature of the sensor industry. This is an industry that is characterized by low to medium product volumes and high levels of product and market specialization. Consequently, it is difficult to attain economies of scale in the sensor industry. A leading manufacturer of piezoelectric sensors with whom TMS has collaborated exemplifies the situation. This company has innovative accelerometer technology well suited to vibration analysis. However, the manufacturing of their products involves low levels of automation, a large amount of manual assembly, and a high degree of custom specialization—all factors that contribute to high prices.

Presently available sensors have very little, if any, local intelligence associated with them. Largely they simply measure a particular parameter and eithe relay that data in real-time to a control booth or store the data for later interrogation. A final illustration of the potential for improved technology came to the authors from an interaction with a leading supplier of valves and other pipeline equipment for such applications as oil refining and natural gas distribution. In this industry a major recent "innovation" was to incorporate a circuit card with a pressure sensor that allowed the sensor to determine whether or not the valve was operating within normal parameters. This improvement resulted in substantial operating cost savings because it eliminated the need to have personnel make a visual inspection of the pressure sensor on a weekly basis. Given the large distances, and numerous valves, involved in something like a natural gas pipeline, the savings can be substantial.

The above examples, although limited, portray the need for condition based maintenance approaches to reducing operating costs and preventing catastrophic failures. Furthermore, they suggest that industry is aware of the potential solutions and has implemented variations thereon in some cases. Widespread adoption of the technology, however, is being limited by the expense of presently available machine diagnostic tools.

Microelectromechanical Technology: A potential solution to the technical and financial dilemmas presented above can be found in the emerging field of microelectromechanical systems (MEMS) [3]. In MEMS integrated circuit processing technology is utilized to fabricate silicon microstructures that are released from the underlying substrate such that they are free to move in one or more dimensions. This technology therefore enables the integration of mechanical (sensors and actuators) and electronic components in a single integrated circuit style device.

Four techniques can be used to fabricate MEMS devices: bulk micromachining, surface micromachining, LIGA (a German acronym Lithographie, Galvanoformung, Abformung, which translates to lithography, electroforming (plating), and molding), and plasma micromachining. Each technique is briefly summarized in Table I. Although each has been successfully used in research programs and in a few initial commercial products, we believe TMS's plasma micromachining has the most promise for new MEMS products, such as those required in machine diagnostics applications, when two practical constraints are considered.

Table I. Summary of MEMS Fabrication Technologies

MEMS Fabrication Technology	Description	Possible Device Geometries	Mechanical Material	Mechanical Structure Aspect-Ratio	Process Integration with Micro-electronics
Bulk micro-machining	Anisotropic chemical etchant (e.g., KOH) is used to define structures bounded by certain crystal planes. Wafer bonding or ion implantation is often used to form etch stops.	very limited shapes; a function of the crystal planes	single crystal silicon	typically low; special cases can be very high	poor
Surface micro-machining	Polycrystalline silicon is deposited on a sacrificial layer of silicon dioxide. Mechanical structures are formed in the polysilicon and then the sacrificial layer is etched away to release them.	arbitrary shapes but limited in vertical height	polycrystal silicon	low	fair
LIGA	Synchrotron x-rays are used to expose very thick resists that are then electroplated or used as a mold for injection molding.	arbitrary	polymer or metal	high	poor
Plasma micro-machining	A sequence of anisotropic and isotropic reactive ion etches is used to fabricate released mechanical microstructures in single crystal silicon.	arbitrary	single crystal silicon	high	excellent

The first constraint is that of process integration. If MEMS devices of reasonable functionality are to be produced at low cost, then eventually the micromechanical devices and the associated electronic components must be integrated on a common chip with a very high yield in manufacturing (>80%). This constraint effectively precludes both the bulk micromachining and LIGA techniques. Bulk micromachining's wet chemical etchants are largely incompatible with pre-existing electronic devices on the wafer. Following etching of thin mechanical devices, the wafers can no longer reliably survive the physical handling inherent in standard automated electronic device fabrication processes. LIGA being a polymer injection molding process (or an electroplating process) has little potential for monolithic integration with silicon-based microelectronic devices.

Surface micromachining is in principle integrable with standard microelectronics fabrication techniques. In practice, however, this turns out to be very difficult to accomplish, particularly with high yields. The wet chemical etch used to remove the sacrificial layer in surface micromachining presents a number of process incompatibilities. Furthermore, the capillary forces generated during removal of the wet etchant often result in deformation of the thin mechanical structures (a failure mechanism known as stiction). Lastly, reproducible fabrication of the polysilicon layer has been found to be difficult in manufacturing. Evidence to date from those companies attempting volume manufacturing of MEMS devices by surface micromachining suggests that this technique cannot attain the required high yield.

The second constraint is that of device performance. A simple geometric factor, the aspect-ratio (height/width) of micromechanical structures plays a critical role in determining the resulting device's performance. Figure 2 defines the parameters of interest for the following calculations in which the role of the aspect-ratio will become clear.

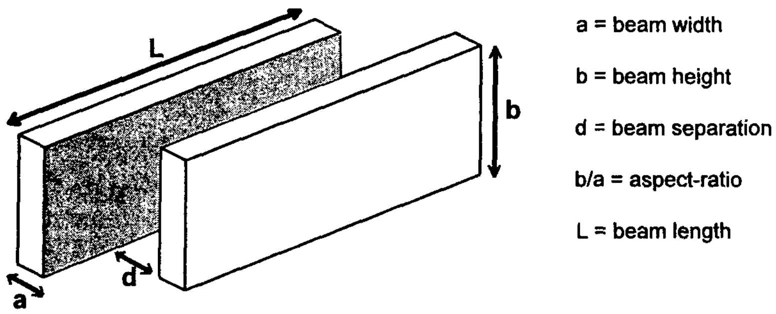

Figure 2. Definition of Key Geometrical Parameters

Many MEMS devices, be they actuators or sensors, involve some form of capacitive device involving pairs of parallel micromechanical beams as conceptually illustrated in Figure 2. If the device is to be used as a sensor, then the capacitance of the structure is the key parameter determining the device's sensitivity. The phenomena to be sensed (force, acceleration, heat, acoustic energy, pressure, etc.) is coupled into the device in such a manner that one plate of the capacitor moves relative to the other. The change in capacitance is used to transduce the motion and hence provides a measure of the desired external stimulus. The capacitance, per unit area of silicon wafer, is given by:

$$C \approx n\varepsilon \frac{b \cdot L}{d} \cdot \frac{1}{a \cdot L} \approx n\varepsilon \left(\frac{b}{a}\right)\frac{1}{d} \qquad (1),$$

where n is the number of plate pairs, and ε is the dielectric constant of the material between the plates, typically air.

If the device is to be an actuator, such as a comb-drive actuator, then the force generated is the key performance factor. The force per unit area of silicon for this type of actuator is given by:

$$F = n\varepsilon \frac{b \cdot V^2}{d} \cdot \frac{1}{a \cdot L} = n\varepsilon \left(\frac{b}{a}\right)\frac{V^2}{d \cdot L} \qquad (2),$$

where V is the voltage applied between the beams.

A final important performance factor is the stiffness of the mechanical structures as this determines the resonant frequency and resistance to motion out of the plane. Higher resonant frequencies increase the operating bandwidth of the device, while high out of plane stiffness precludes unwanted mechanical modes. The stiffness of a micromechanical beam loaded at its midpoint is given by:

$$K = \frac{48 \cdot E \cdot I}{L^3} \cdot = \frac{4 \cdot E}{L^3} \cdot a^3 \cdot b \qquad (3),$$

where E is the Young's modulus of the material and I is the moment of inertia.

The calculations presented above for sensing capacitance and actuating force were stated as per unit area of silicon. The relevance of this quantity is that the manufacturing yield of a silicon IC chip in conventional microelectronic device processing is essentially inversely proportional to the area of the chip. The larger the chip size, the lower the yield per wafer. Hence, capacitance or force per unit chip area provides a means for comparing surface and plasma micromachining for comparable manufacturing yields.

In surface micromachining, the height of the mechanical structures (b) is determined by the thickness of the polycrystalline silicon film deposited. Residual stress in polysilicon films establishes a practical limit of 2-5μm for their height. Whereas in plasma micromachining, the height of the structures is determined by the depth of the reactive ion etch. In practice these heights can be as much as 20μm. Recent research [4] advances in plasma micromachining suggest the possibility of structures in single crystal silicon as high as 100μm.

The beam width (a) and separation (d) are determined by lithography in either surface or plasma micromachining. Both techniques can attain minimum feature sizes of 2μm and below. Hence, the key distinction between surface and plasma micromachining is the greater beam heights and aspect-ratios attainable in the latter. A factor of ten higher beam height for plasma micromachining (e.g., 20μm versus 2μm) results in sensing capacitance and actuating force per unit area of silicon ten times that available with surface micromachining. Table II provides some representative values. The significant advantages of plasma micromachining are clearly illustrated in the right-hand column of the table.

Table II. Representative MEMS Geometries and Device Parameters for Surface and Plasma Micromachining

	Surface Micromachining (published Analog Devices process[5])	**Plasma Micromachining** (same parameters as previous column other than aspect ratio)	**Plasma Micromachining** (using typical process capabilities)
Beam width (a)	4 μm	4 μm	1.5 μm
Beam height (b)	2 μm	20 μm	20 μm
Beam separation (d)	1.3 μm	1.3 μm	1.0 μm
Beam length (L)	120 μm	120 μm	250 μm
Number of pairs (n)	46	46	100
Actuator voltage (V)	24 V	24 V	24 V
Device capacitance (C)	0.07 pF	0.74 pF	4.4 pF
Device actuating force (F)	0.37 μN	3.6 μN	10.2 μN
Single beam stiffness (K)	56.3 N/m	563 N/m	3.3 N/m

Plasma Micromachining: The foregoing analysis of MEMS device performance and process integration clearly suggests that plasma micromachining offers the best potential for commercially viable MEMS products. This proprietary process [6] largely developed by researchers at Cornell University [7] has been licensed exclusively to TMS Technologies.

In plasma micromachining all of the mechanical structures are fabricated in single-crystal silicon using dry etching (plasma-etching) techniques. The process is fully compatible with conventional integrated circuit processing, enabling easier integration of mechanical devices with microelectronics for control and signal processing. Even more significant, the process can fabricate mechanical devices onto a pre-existing integrated circuit wafer without damaging the electronics. This is possible because no high temperature steps, which would ruin existing metal interconnects, or wet chemical etches, are necessary to produce the mechanical structures.

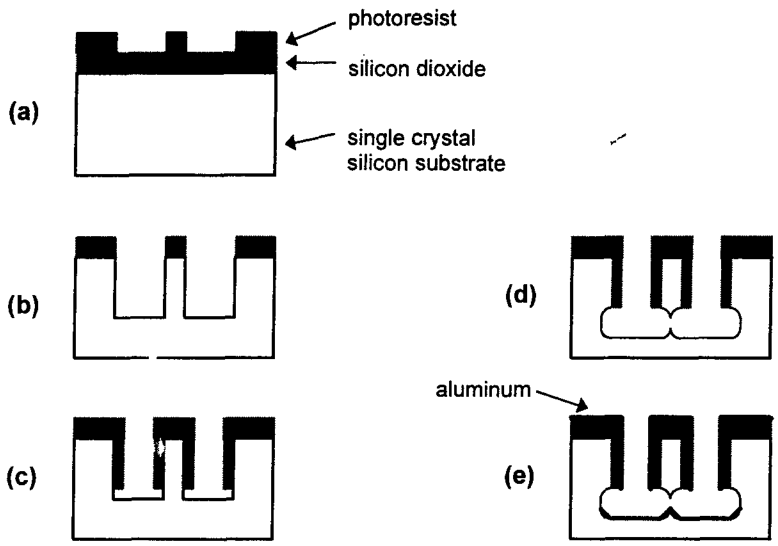

Figure 3. Illustration of Plasma Micromachined Silicon MEMS Process

The basic, single-mask, TMS micromachining process is illustrated in Figure 3. Photoresist is deposited and patterned on top of a layer of silicon dioxide (a). After the pattern is transferred using reactive ion etching, the silicon dioxide serves as a hard mask during a deep silicon trench etch (b). A layer of silicon dioxide is conformally deposited over the entire structure, and unwanted oxide on the floor of the trenches is removed using another reactive ion etch step (c). The silicon mesa, to become a released cantilevered beam, is undercut with a nearly isotropic reactive ion etch. The etch undercuts those areas not protected by silicon dioxide, leaving the beam in the center free to move laterally (d). Finally, a self-aligned metal layer is deposited over the entire structure to provide electrical connection (e).

Figure 4 is an electron micrograph showing some of the mechanical structures that can be fabricated with the plasma micromachining process. Illustrated in this figure are the high aspect ratio beams referred to earlier. The separation of the beams from the substrate is clearly visible.

Conclusions: Structures such as those shown in Figure 4 form the basis for micromechanical accelerometers which can be used in vibration analysis. These devices are capable of measuring acceleration over a wide range (fractions of a g to hundreds of g's) and can incorporate sophisticated electronics for signal conditioning and local information processing. In addition to vibration analysis, MEMS based sensors can be developed to measure a wide range of relevant operating parameters including pressure, temperature, rotation, and the like. From a practical perspective, integrated microelectromechanical sensors offer the opportunity to bring low cost, high volume integrated circuit manufacturing techniques to the sensor industry. This merger of fields can result in cost effective sensor technologies that will catalyze the use of new condition based maintenance techniques in industrial applications.

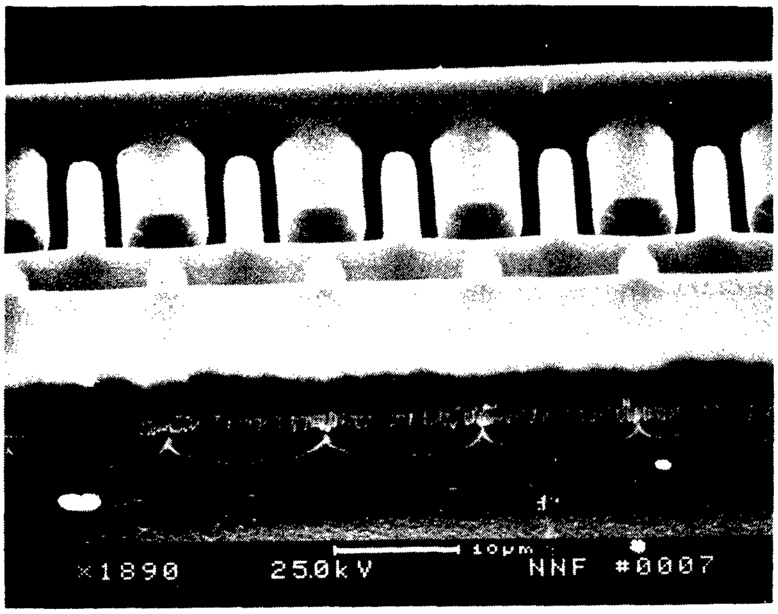

Figure 4. TMS Plasma Micromachined MEMS Structures

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